

The Parton-Hadron Phase Transition in Central Nuclear Collisions at the CERN SPS *

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Abstract

A selection of recent data referring to $Pb + Pb$ collisions at the SPS CERN energy of 158 GeV per nucleon is presented which might describe the state of highly excited strongly interacting matter both above and below the deconfinement to hadronization (phase) transition predicted by lattice QCD. A tentative picture emerges in which a partonic state is indeed formed in central $Pb + Pb$ collisions which hadronizes at about $T = 185\text{ MeV}$, and expands its volume more than tenfold, cooling to about 120 MeV before hadronic collisions cease. We suggest further that all SPS collisions, from central $S + S$ onward, reach that partonic phase, the maximum energy density increasing with more massive collision systems.

1 Relativistic Nuclear Collisions

Astrophysical objects and processes, both connected with very early and very late phenomena in the cosmological evolution of strongly interacting matter, present an enormous challenge to modern nuclear and particle physics: we can recreate the conditions prevailing during the late nanosecond era of the cosmological expansion (when free quarks and gluons hadronized to isolated protons and neutrons), or during the late stages of a violent supernova stellar implosion (when the properties of highly compressed nuclear matter decide the final avenue leading either into a superdense neutron star or into a black hole) in experiments carried out in the terrestrial laboratory, by colliding heavy nuclei at relativistic energy. These studies culminate, for the time being, in the CERN SPS ^{208}Pb beam facility which accelerates Pb nuclei to 158 GeV per nucleon (about 33 TeV total energy). Ongoing programs at BNL and CERN will vastly extend the energy domain from $\sqrt{s} \approx 17\text{ GeV}$ at the SPS to collider mode experiments with $\sqrt{s} = 200\text{ GeV}$ (RHIC) and $\sqrt{s} \approx 5\text{ TeV}$ (LHC).

The common idea of these investigations is to create extended "fireball" volumes of strongly interacting matter in head-on collisions of heavy nuclei, creating an average energy density reaching (at the SPS) or far exceeding (at RHIC and LHC) the "critical" value of about $1.5\text{ GeV}/fm^3$, at which modern Lattice QCD theory predicts a sudden departure, concerning the specific heat, the number density of degrees of freedom, the constituent quark mass scale etc., away from the expected behaviour of a densely packed liquid of hadrons. Does the hadron degree of freedom melt away at this transition point, giving rise to a continuous QCD state in which massive "constituent" quarks turn into nearly massless "current" (QCD) quarks - a phenomenon associated with the concept of chiral symmetry restoration - and in which colour carrying partons acquire a finite mobility, i.e. they approach deconfinement in an extended plasma state of *nuclear* dimension, i.e. 10 fm , large in comparison to typical confinement scales of about 1 fm .

The present state of the art in lattice QCD finite temperature calculations [1] is illustrated in *Fig. 1*. On an $8^3 \times 4$ lattice with two dynamical quark flavours, the Wilson loop L and the effective quark mass scale

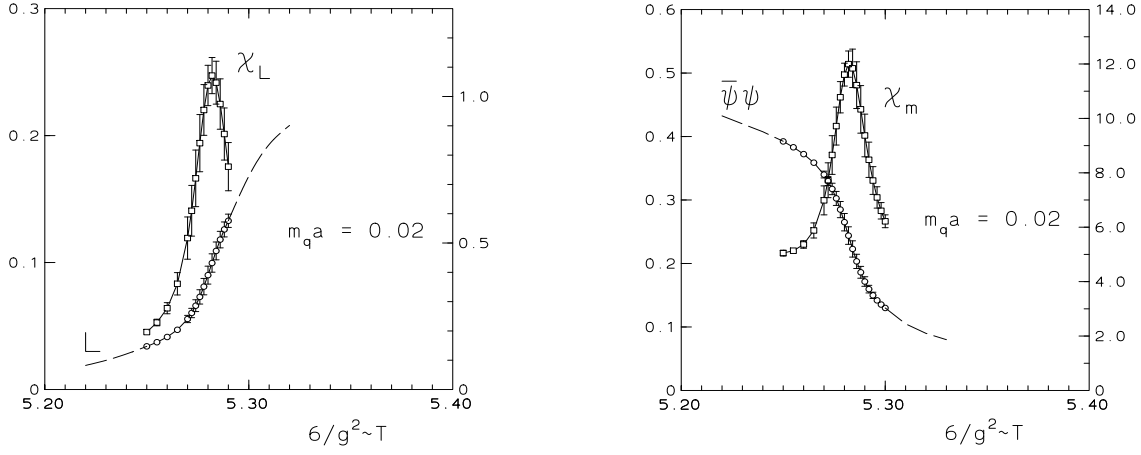


Figure 1: Lattice QCD results for the Wilson loop L and the quark mass scale $\langle \bar{\Psi}\Psi \rangle$ vs. $6/g^2$ with g the lattice coupling constant.

$\langle \bar{\Psi}\Psi \rangle$ are calculated along with the corresponding generalized susceptibilities. The quantity L depends on the free quark energy, $L \approx \exp[-F/T]$, and can be understood as a measure of colour mobility vs. colour confinement. A sharp jump occurs as the temperature given in units of the inverse lattice coupling constant g reaches a critical value (note the very narrow scale), suggesting a phase change or a phase transition. At exactly the same position the quark mass (the "quark condensate") drops steeply. This suggests that quarks and, hence, hadrons loose their mass at a critical temperature T_c , and simultaneously acquire a finite free energy in the medium, resulting in a finite mobility which indicates deconfinement. This interpretation is supported by a concurrent steep jump in the energy density E/T^4 (not illustrated). We thus expect a new QCD phase of matter setting in at $T_c = 160 - 200 \text{ MeV}$ which exhibits a critical energy density of 1.5 to $3.0 \text{ GeV}/fm^3$.

How to search experimentally for this new phase? In the following chapters I will consider some of the appropriate physics quantities, and present relevant data stemming from central collisions of SPS sulphur (^{32}S) and lead (^{208}Pb) beam projectiles with various nuclear targets. At first we may ask whether the critical energy density is reached (or even surpassed) in the primordial interaction volume. The conclusion is affirmative as will be described in Section 2. The interaction volume may reach energy densities characteristic of a partonic, extended system. The immediate next question concerns observables that respond directly to a transient, deconfined state (ideally a quark-gluon-plasma state): Section 3 establishes the J/Ψ production yield as one of the most informative, relevant observables, concluding that the data appear to be compatible with the hypothesis of deconfinement reached in central $Pb + Pb$ collisions. The suppression of the J/Ψ yield, however, answers merely the "to be or not to be" question of deconfinement. Supposing that a deconfined, partonic state was indeed created in the primordial reaction volume, at the maximal energy density attainable in CERN SPS collisions, the next equally important question concerns observables elucidating the nature of the parton to hadron phase transition occurring in the dynamical evolution during which the primordial interaction volume expands, the energy density falling toward the critical density of the QCD hadronization point. I propose that bulk hadron production data hold the promise to elucidate the conditions prevailing at the phase transition. In Sect. 4 the implications of strangeness production data will be discussed. Sect. 5 presents an analysis of hadronic yield ratios that

are shown to refer directly to the conditions prevailing at the hadronization point. In Sect. 6 I turn to hadronic spectra and Bose-Einstein correlation data pointing out their potential information content regarding the overall partonic-hadronic dynamical trajectory of the interaction volume. Sect. 7 gives a short summary.

2 Transverse Energy Density Estimates

The prediction of lattice QCD puts the phase transition between hadrons and partons at about $1.5 \text{ GeV}/fm^3$, not implausible as this is the energy density in the deep interior sections of hadrons where partons are similarly deconfined albeit in a small volume. It is the first task of relativistic nuclear collisions to demonstrate that energy densities upward of $1.5 \text{ GeV}/fm^3$ are indeed created in central collisions. To this end one measures the rapidity distribution of total transverse energy production in calorimeters, then to relate the rapidity density dE_T/dy to the spatial density ϵ in a formalism developed by Bjorken [2]:

$$\epsilon = [dE_T/dy] [\pi R^2 l]^{-1}. \quad (1)$$

Employing the Bjorken estimate with a primordial radius $R(^{208}Pb) = 1.16 \cdot A^{1/3}$, and a formation time $l = 1 fm/c$, the NA49 calorimetric results for the energy density near midrapidity were [3]: $\epsilon=1.3$ (central $S + S$ at 200 GeV) and 3.2 (central $Pb + Pb$ at 158 GeV) (in GeV/fm^3), i.e.

$$\epsilon(Pb + Pb) \approx 2.5\epsilon(S + S). \quad (2)$$

In this estimate taking the Woods-Saxon-radius of Pb instead of the *rms* radius (smaller by about $\sqrt{2}$) leads to a low value, but taking $l = 1 fm/c$ (could be up to $l = 2 fm/c$) to a high value. The combined choices thus appear reasonable.

At QM 96 both Kharzeev, and Blaizot and Ollitrault [4] have pointed out that this is the *average* density of the source volume. The *central* energy density is higher by perhaps 1.5 depending on one's picture of the radial density profile. $Pb + Pb$ may thus reach about $4.0 - 4.5 \text{ GeV}/fm$ in the extended interior sections. But the ratio $\epsilon(Pb)/\epsilon(S) \approx 2.5$ independent of these considerations. Thus the "interior" of $S + S$ (if existing) will provide about $1.6 \text{ GeV}/fm^3$. The Bjorken estimate refers to an ultra-relativistic collision scenario supposing a boost invariant, longitudinally expanding tube of partonic matter. At the modest SPS $\sqrt{s} \approx 20 \text{ GeV}$ we are, not quite, at this ideal limit. The domain of approximate boost invariance shrinks to a relatively narrow interval in longitudinal phase space, $|y_{cm}| \leq 1$. We focus on that interval in turning from global, calorimetric E_T data to energy density estimates based on the momentum space distributions of identified hadrons. From NA49 charged hadron production 4π data, Günther [5] gets $\epsilon = 2.16 \text{ GeV}/fm^3$, for pions + net baryons in central $Pb + Pb$ near mid-rapidity. Estimate the additional kaon + newly created baryon-antibaryon fraction to add about 15-20%:

$$\epsilon(Pb + Pb)_{y \approx y_{mid}} = (2.6 \pm 0.3) \text{ GeV}/fm^3, \quad (3)$$

not so bad an agreement between tracking and calorimetry. We may obtain a third estimate from the observations that

1. The distribution of net baryons is quasi-flat in $2 < y < 4$ and

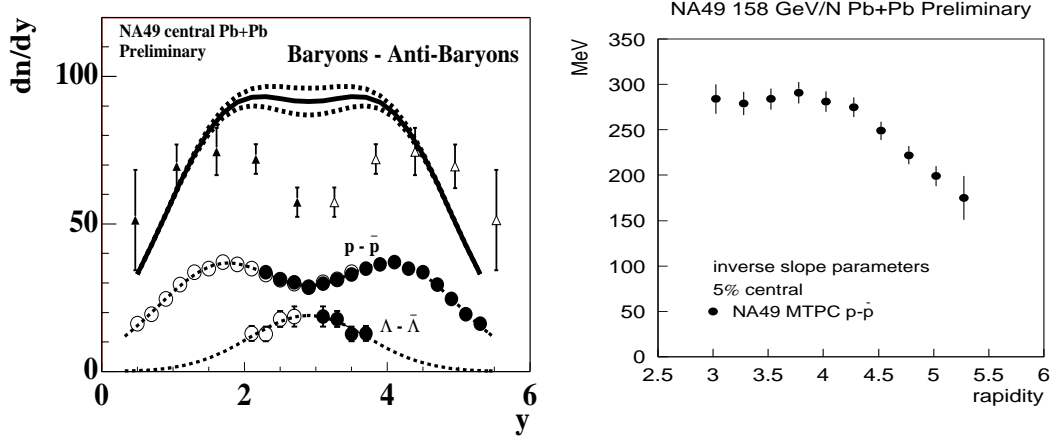


Figure 2: Rapidity distribution of participant baryons in central $S+S$ (triangles scaled up by 7) and $Pb+Pb$ collisions (left), and inverse slopes of proton transverse mass distribution as a function of rapidity (right) [5, 6].

2. The net "proton" m_T -spectral slopes are quasi-constant in $3 < y < 4$.

These NA49 data [5, 6] are illustrated in *Fig. 2*.

From this we may infer that the primordial hadron or parton source is, in rough approximation, a cylinder with Pb -radius extending from $y = 2$ to 4. Assume further that this cylinder "radiates" the entire transverse energy content of the system, as seen in NA49 calorimeter data [3]: $E_T^{tot} = (1.0 \pm 0.1) TeV$, for central $Pb + Pb$.

Now make a Bjorken-like estimate for the spatial volume of that cylinder: assume $\langle R(Pb \text{ Woods-Saxon}) \rangle = 6 fm$ at $\langle b \rangle = 2.0 fm$ (the NA49 centrality trigger [3]); assume that one rapidity unit corresponds to a longitudinal extension equal to the formation length for which I now take $l = 1.5 fm$:

$$V_{cylinder} = \pi R^2 l \cdot \Delta y = 340 fm^3 \quad (4)$$

$$\epsilon_{average} = (2.9 \pm 0.3) GeV/fm^3 \quad (5)$$

in central $Pb + Pb$. Overall (from the 3 estimates) we get for the average

$$\epsilon(Pb) = (2.9 \pm 0.4) GeV/fm^3. \quad (6)$$

In summary: Kharzeev, Blaizot and Ollitrault [4] may be right in estimating the *interior* $Pb + Pb$ energy density to be about $4 GeV/fm^3$. It would then be about $1.6 GeV/fm^3$ in $S + S$. Thus the latter system may just approach the critical QCD energy whereas all the above estimates indicate that the fireball created at mid-rapidity in central $Pb + Pb$ collisions exhibits energy density beyond the realm of matter consisting of hadrons.

3 Lattice QCD and Debeye-Screening of J/Ψ and Ψ'

From QCD we need to recall two predictions: First, look at recent estimates of the critical energy density at which the parton \leftrightarrow hadron phase change occurs. It has continuously come down over the last 5 years,

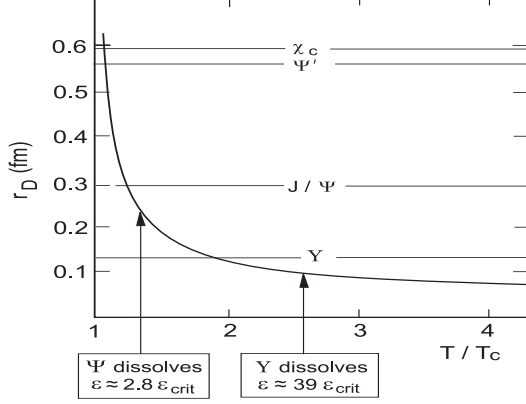


Figure 3: Debye screening radius from QCD [8] versus temperature in units of T_c .

to [1]

$$\epsilon^{crit}(QCD\ lattice) = (1.5 \pm 0.5) GeV/fm^3. \quad (7)$$

F. Karsch [7] even gets $1 GeV/fm^3$. Second, however, it is important to recall here the earlier estimates [8] of the QCD "Debye screening" length (i.e. the length scale at which QCD acquires an effective short range interaction form) as a function of energy density. More than a decade ago Matsui and Satz [8] argued that QCD bound states (hadrons) should dissolve once their radius exceeds the screening length. They pointed out the small radius J/Ψ vector meson as a suitable tracer hadron, to monitor QGP plasma conditions attained in nuclear collisions.

Fig. 2 shows results presented in the book "Quark Matter I" edited by R. Hwa [9]: The screening length r_D falls steeply with T/T_c . For the large Ψ' we see $r_D \approx r(\Psi')$ already at $T = T_c$, but $r(J/\Psi) \approx 0.5 r(\Psi')$ and thus screening (disruption) of J/Ψ occurs at $T/T_c \approx 1.3$. This seems little difference but recall the plasma energy density ϵ proportional T^4 to first order:

$$\text{thus } \Psi' \text{ melts at } T_c \text{ at which } \epsilon = \epsilon^{crit} \approx 1.5 GeV/fm^3$$

$$\text{but } J/\Psi \text{ melts at } 1.3 T_c, \epsilon = 2.86 \epsilon^{crit} \approx 4.3 GeV/fm^3.$$

Our above estimates of energy density thus lead us to expect that Ψ' yields are suppressed already in intermediate mass collisions, whereas the J/Ψ yield gets critically suppressed in central $Pb + Pb$ collisions only. This expectation is in fact borne out by NA38/50 data for Ψ' and J/Ψ suppression [10]. NA38 reported Ψ' suppression to be "complete" already in semi-central $S + W$ (roughly comparable to central $S + S$). NA50 reported J/Ψ suppression to start becoming "complete" in central $Pb + Pb$ only (we ignore here the details [11] of the much-discussed dependence, differentially, on system size or E_T scales in NA38/50 data). These data are illustrated in *Fig. 4*.

With "complete" I refer to "maximum possible" suppression: the yield can never go to zero because of the unavoidable surface regions, at low ϵ , present in all collision geometries! A provocative conclusion results: From lattice QCD Ψ' suppression says we are at (or slightly above) T_c and at (or slightly above) $\epsilon^{crit} \approx 1.5 GeV/fm^3$. Indeed NA35/49 estimates [3] for central $S + S$ or semi-peripheral $S + A = 200$: $\epsilon \approx 1.6 GeV/fm^3$, and NA38 sees that Ψ' disappears here. This agreement, by itself, presents no strong argument as breakup of the large, weakly bound Ψ' could also occur in hadronic matter at this energy density. However the onset of a disappearing J/Ψ yield in central $Pb + Pb$ (*Fig. 4*) signals that we are

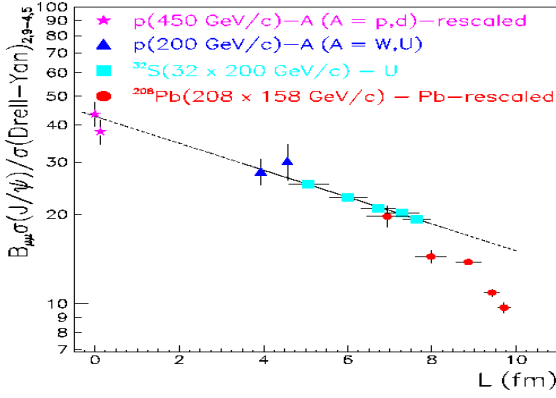


Figure 4: J/Ψ production relative to the Drell-Yan yield. Data for proton, sulphur and lead induced collisions are shown from NA38,50,51. They are plotted against the effective thickness of the collision system. All data fall onto the 6 mb breakup line [12] except for the central $Pb + Pb$ collisions which exhibit additional suppression.

near $\epsilon = 4 \text{ GeV}/fm^3$ here, in agreement with the above estimates of ϵ . Invoking the effect of hadronic co-movers is completely implausible here because the forbiddingly high packing density (several "hadrons" per fm^3) renders hadronic transport or cascade models meaningless. We conclude that these observations point to the existence of a non-hadronic phase.

4 Total Strangeness Yield and Strange/Entropy Ratio

From now on I will tentatively take for granted the above indications that in central $S + S$ we are at (or slightly above) T_c whereas with increasing system size we end up at about $1.3 T_c$ in central $Pb + Pb$, the interior energy densities ranging up to about $4 \text{ GeV}/fm^3$, where a partonic phase is realized. Are other observed signals compatible with this hypothesis? I turn now to bulk hadron production data to show that this is indeed the case. Let us first recall the NA35/49 results concerning strangeness production.

The abundance of $s + \bar{s}$ relative to $u + \bar{u} + d + \bar{d}$ at or near hadronization can be estimated by "Wroblewski" quark-counting [13]; this estimate starts from the observed strange to nonstrange hadron production ratio in 4π . It can be approximated by the measured K/π and Λ/π ratios [14]. The NA35/49 data show that the K/π ratio stays *near constant* in central $S + S$, $S + Ag/Au$ and $Pb + Pb$ [6, 14, 15]. The yields and yield ratios of strange and nonstrange hadrons in $S + S$ [14] and $Pb + Pb$ [6] exhibit a near perfect hadrochemical equipartition in phase space. The analysis by Becattini et al. [16] shows that all final yields (extrapolating to early times by inclusion of all resonance decays a la Wroblewski) resemble a thermal "family" of hadrons at $180 < T < 190 \text{ MeV}$, for all SPS reactions from $S + S$ to $Pb + Pb$. *However this family can only be consistently described by making the additional assumption that the strangeness content is universally underpopulated*, at 60-70% only of the global equilibrium abundance in a hadronic "reactor vessel" at these temperatures. Essentially no change from $S + S$ to $Pb + Pb$, like in the K/π ratio. These results are illustrated in Fig. 5. In order to build a conclusion on these observations consider the model formulated by Kapusta and Mekjian [17]. They derive estimates for the dynamical equilibration (relaxation) times of quark flavours in a model quark gluon gas and in a hadronic reactor, and they derive predictions for the equilibrium abundance ratios of K/π (an observable that they link to the "strangeness to entropy ratio").

Fig. 6 shows their estimates for the equilibration time constant vs. temperature, in a QGP and in a hadron gas. We assume now that the critical temperature is $T_c = 185 \pm 15 \text{ MeV}$, and that, in central $Pb + Pb$, we are starting from a primordial state at $T \approx 1.3 T_c = 240 \text{ MeV}$. The relaxation time is of

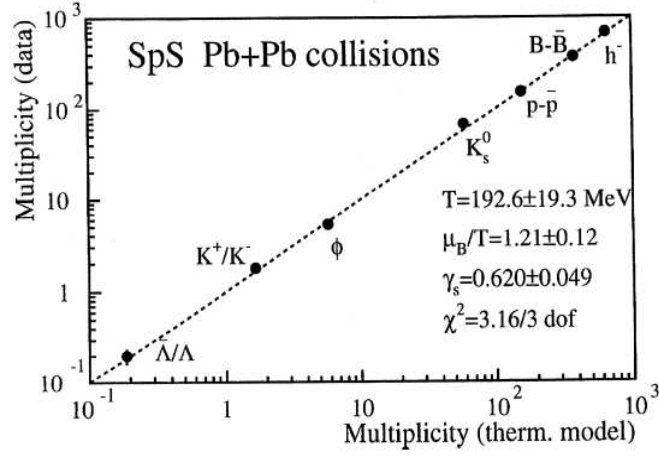


Figure 5: Comparison of hadronic yields and yield ratios in central $Pb + Pb$ collisions with predictions of the thermal model [16]. The parameter γ_s represents the degree of strangeness saturation.

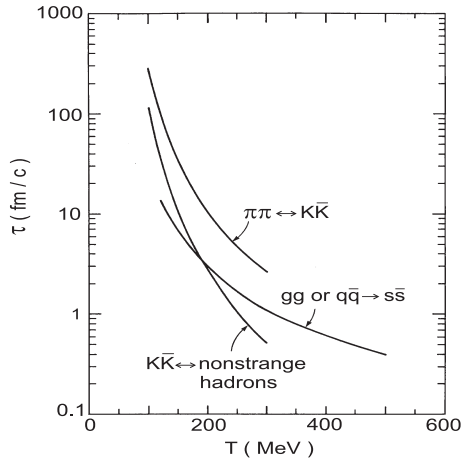


Figure 6: Relaxation time constants [16] for hadrons and partons as a function of temperature

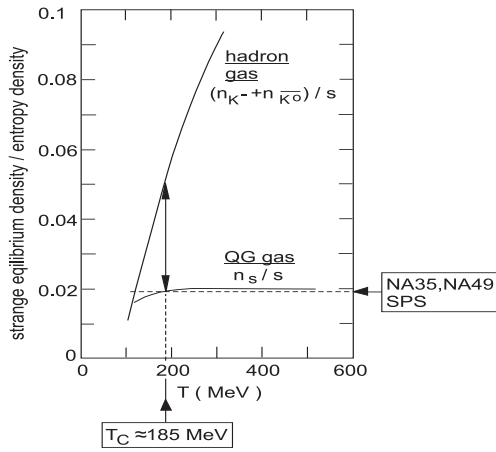


Figure 7: Equilibrium ratio of strangeness to entropy [16] in a partonic and hadronic scenario

order $\tau = 1 fm/c$ in both systems at the latter temperature: comparable to Bjorkens formation time! The strange to nonstrange content of the reactor vessel must therefore be near equilibrium at the instant of particle formation under such circumstances, both for a hadronic or partonic state. *Fig. 7* shows the ratio of strangeness to entropy abundance, essentially translating into the K/π ratio. If the primordial state at $T = 240 MeV$ was in the hadronic phase, the equilibrium ratio would be about 3.5 times higher than in the partonic phase, and a huge $s + \bar{s}$ population would result. Upon expansion we reach $T = T_c \approx 185 MeV$ where the population would still exceed the QGP population ratio by a factor of about two. Note that the latter ratio is constant! No variations of K/π are seen in the data, which are near a value of 0.15 for all systems and agree with the "QGP" level [18]. Furthermore, *Fig. 6* shows that the relaxation time $\tau > 3 fm/c$ below $T = 185 MeV$, rapidly increasing with temperature falling further: it appears unlikely that the observed ratio K/π is much altered by anything that happens below $T = 185 MeV$. Indeed the Becattini model (*Fig. 5*) finds $T = 190 \pm 20 MeV$.

We are lead to the conclusion that the system was not in a hadronic phase at its maximum energy density, neither in $S + S$ nor, of course, in $Pb + Pb$ because it would then have no reason to be strangeness-undersaturated. If it was in a partonic phase (represented in *Fig. 7* by the thermal parton equilibrium state "QG-gas") its K/π yield would be constant throughout, and near the value observed by NA49 as Sollfrank et al. have shown [18]. As the "QG-gas" hadronizes at $T = 185 MeV$ it does not bring sufficient strangeness into the emerging hadron phase which, if in global flavour equilibrium by itself would feature about twice the strangeness content from *Fig. 7*. However *Fig. 6* indicates that the hadronic phase would take upward of $3 fm/c$ at constant $T \approx 185 MeV$ to equilibrate strangeness. This time is not available owing to the rapid expansion prevailing at hadronization time. The hadronic phase will, thus, evolve essentially preserving its pre-hadronic strangeness input. The NA35/49 strangeness data thus appear to agree qualitatively with expectations from a simple model for a parton to hadron phase transition occurring at $T \approx 185 MeV$ from $S + S$ to $Pb + Pb$ [18].

Note that in these thermal models [14,16,17,18] one employs hadronization temperatures of up to $190 MeV$ without wondering about the classical Hagedorn limit for the hadronic temperature, of about $165 MeV$. Future models that incorporate the hadronic eigenvolume may thus drastically change our views [19]. Furthermore, hadrons need not to be in their vacuum configurations [20] at the high hadronic densities prevailing at hadronization (contrary to what is assumed in all hadro-chemical models). These observations keep us, for the present time, from a firm claim that the strangeness to entropy data imply discovery of the QCD partonic phase. They are, however, compatible with this hypothesis.

I also wish to note here that the term "thermal model" refers to statistical phase space descriptions that differ in detail. The Becattini model [16, 18] maintains the strangeness saturation parameter γ_s in keeping with the Wroblewski analysis [13] of hadronic collisions where strangeness is manifestly undersaturated ($\gamma_s = 0.3 - 0.4$). For $Pb + Pb$ this model still suggests a significant deviation from unity ($\gamma_s = 0.62$): primordial strangeness is enhanced relative to $p + p$, $p + A$ and $e^+ + e^-$ collisions at similar energy but still significantly undersaturated in a hypothetical global equilibrium state at the hadronic side of the phase transition. *Fig. 8* illustrates these observations in the framework of the thermal model [16, 18]. They are cast here into the variable suggested by Wroblewski [13]: strange to non-strange quark abundance at the

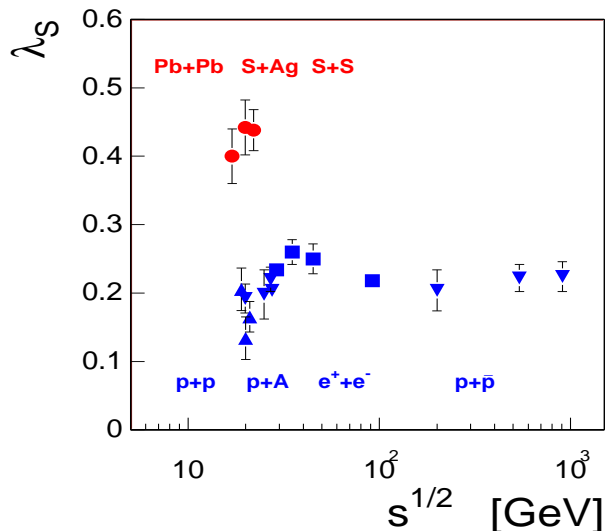


Figure 8: The ratio of strange to non-strange quarks, $\lambda_s = (s + \bar{s})/2(u + \bar{u} + d + \bar{d})$ in nucleus-nucleus collisions and elementary collisions [16].

state at hadronization.

In the next section we shall suggest that the hadronic population ratios are the result not of a rescattering equilibrium state created in the early hadronic phase but of the hadronization mechanism. Strangeness undersaturation results from the partonic strangeness levels, in this picture, and central nuclear collisions exhibit drastic differences from, e.g. e^+e^- regarding their primordial strangeness population, as seen in *Fig. 8*. However, other thermal models for SPS collisions dispense with the additional parameter of strangeness saturation [21] still obtaining reasonable fits to the hadronic production ratios. The eventual decision concerning strangeness as a diagnostic of the flavour composition prior to hadronization will come from new precision data [22] on hyperon production ($\Lambda(1520), \Xi, \Omega$). In fact Bialas [23] has just shown that the observed hyperon to antihyperon yield ratios can be well understood in a flavour coalescence model (see next section) based on the partonic strangeness concentration.

5 Hadronization and apparent Hadrochemical Equilibrium

5.1 Origins of Equilibrium

The observation of an apparent thermal equilibrium among hadronic species has baffled particle physicists since Hagedorn's times. As I have made ample reference to such models above I insert a section to attempt a qualitative explanation, in a scetchy manner. Let me note, first, that chemical equilibrium among a mixed phase of inelastically interacting hadronic species represents, not at all a difficult situation but the maximum entropy state (minimum information): the state of *highest* statistical probability. In a multiparticle inelastic collision far above thresholds the key question must be (opposite to the traditional approach) what could keep the system from realizing that state. We will show in sec. 6 that the very fast, "explosive" expansion mode observed at SPS energy indeed prohibits hadro-chemical equilibration by rescattering. Nevertheless the concept of chemical equilibration as a limit of multiple inelastic rescattering cascades is the presently most persued point of view. The dominance of this view is due to theoretical

implementation in microscopic cascade models which have shown that, at modestly relativistic energy, the lowest modes of hadronic matter can indeed acquire equilibrium due to rescattering in central heavy nucleus collisions [24].

However this "rescattering paradigm" must lead to deep skepticism concerning equilibrium concepts once the collision energy increases (dominance of longitudinal motion), from $\sqrt{s} \approx 2.5 \text{ GeV}$ at Bevalac/SIS to $\sqrt{s} = 20 \text{ GeV}$ at the SPS. Furthermore a hadronic rescattering mechanism is obviously inapplicable once we turn to individual hadron or lepton collisions. The apparent success of Hagedorn analysis at $\sqrt{s} \geq 8 \text{ GeV}$ would, thus remain a mystery. However this analysis turns out to be even more satisfactory once the energy increases, and e^+e^- LEP collider data for Z^0 decay to hadrons at 92 GeV exhibit perfect equilibrium populations of about 20 hadronic species [25]. The temperature from the fit is 190 MeV , the same as in $Pb + Pb$ (Fig. 5)! But the strangeness undersaturation factor is more prominent, $\gamma_s = 0.4$. Obviously these observations are incompatible with the hadronic rescattering paradigm.

There must thus be another way to create a hadrochemical equilibrium state at $T = 185 \text{ MeV}$. The answer has been indicated by Geiger and Ellis [26]: the *hadronization process* enforces phase space dominance due to its combined non-perturbative mechanisms. This view has first been presented by Knoll et al. [31] Geiger and Ellis studied similar LEP data as Becattini [16], W^{+-} to hadrons, in a partonic transport model which ends in hadronization. The latter is treated as a multiple "coalescence" in which the right combinations of partonic spin, flavour and colour are combining to form colour neutral pre-hadrons (heavy resonances that decay instantaneously). The observed hadron production yields are well accounted for, and the authors note a remarkable insensitivity regarding the detailed assumptions made for the hadronization mechanisms. The final multihadronic state is thus *born into equilibrium* (i.e. at maximal entropy), out of the partonic phase.

A tantalizing conclusion results. If SPS $Pb + Pb$ central collisions create a partonic initial phase we should observe similar hadronic population ratios as in the LEP data, as a consequence of the system evolving through a parton to hadron phase transition. This is indeed the case (Fig. 5 for $Pb + Pb$)! In this view, the increase in γ_s from 0.4 to 0.62 and the upward jump λ_s (Fig. 8) *results from differences in the partonic phase*, between the e^+e^- single initial "string" and the large transverse dimension in the nuclear collision. No new strangeness is created in the Geiger-Ellis model, in the process of hadronization.

Geiger and Srivastava [27] have recently been daring enough to apply this model to SPS central $Pb + Pb$ collisions. They conclude that there are remaining remnants of projectile-target structure functions but that the hadron yield near midrapidity stems mostly from a parton cascade to hadronization process. In fact they are able to reproduce the proton to negative hadron to kaon ratios reported by NA49 [6]. Of particular interest in view of our discussion in sections 2 and 3 is their result for the overall time dependence of the energy density in an interior subvolume of 4 fm transverse extension near midrapidity, as reproduced in Fig. 9. The partonic phase exhibits $\epsilon > 2 \text{ GeV}/\text{fm}^3$ until about $\tau = 2 \text{ fm}/c$; hadronization begins after a formation time of about one fm/c and the hadronic phase ends at $\tau \approx 20 \text{ fm}/c$ where $\epsilon < 0.2 \text{ GeV}/\text{fm}^3$. The initial energy density amounts to $4 \text{ GeV}/\text{fm}^3$. All this agrees with our above guesses. In particular there are no hadronic co-movers to a $c\bar{c}$ pair of any significant density, as to break up the emerging J/Ψ signal. The hadronic fraction never exceeds an energy density of $0.5 \text{ GeV}/\text{fm}^3$. Note that this model

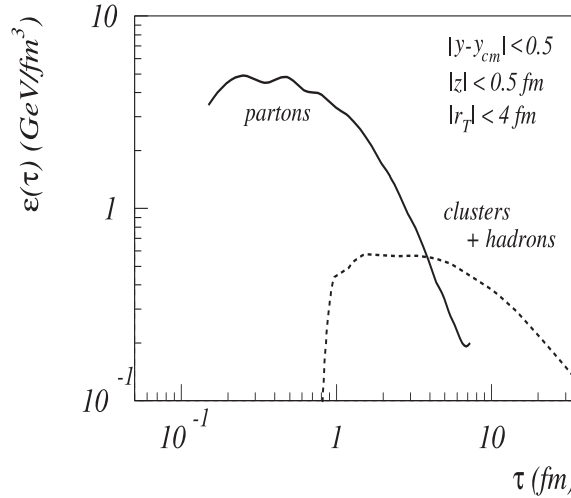


Figure 9: Energy density for central $Pb + Pb$ at SPS from the parton transport and hadronization model of Geiger and Srivastava [27].

does thus not predict an unreasonably high hadronic density during the hadronization phase, apparently due to the long duration ($4 - 5 \text{ fm}/c$) of the hadronization transition: hadrons can escape in transverse direction, creating a radial expansion velocity pattern (see next section).

We conclude that hadronic equilibrium populations at temperatures as high as 185 MeV can be understood as a fingerprint of QCD hadronization. In this view the multihadronic final state is not the result of cascade inelasticity. The rigid fixation of $T \approx 185 \text{ MeV}$ conditions throughout the reaction volume (which must have significant primordial variation of energy density due to impact geometry) stems from the universal avenue through hadronization which occurs at a rigidly fixed energy density.

5.2 Analysis of Single Events

If the above line of argument is correct we have thus located the QCD phase boundary at $T \approx 185 \text{ MeV}$ for a baryochemical potential of $\mu_B \approx 0.25 \text{ GeV}$, specific for the conditions reached in central S and Pb induced collisions at top SPS energy. From similar analysis of multi-hadronic final states created in LEP Z^0 decays we infer that the transition "temperature" is about the same at $\mu_B = 0$. This indicates a *universal* influence of the non perturbative QCD hadronization mechanism at sufficiently high \sqrt{s} , and at low values of μ_B . What, then, is specific to central nuclear collisions? Let me proceed in two steps.

First, there can be no doubt that an e^+e^- generated Z^0 decay "string" of 92 GeV constitutes an ideal QCD excitation object free of net quantum number constraints and structure function remnants, clearly of strictly partonic composition, which must hadronize and, thus, reveal QCD hadronization features. The emphasis in the line of argument in sections 4 and 5 is to demonstrate that $Pb + Pb$ at $\sqrt{s} = 17 \text{ GeV}$ shows similar hadronization features and might thus also result from a partonic phase. This is a totally non-trivial proposition as the elementary baryon collisions at this \sqrt{s} should have an average parton-parton \sqrt{s} of about 3 GeV only, and the dynamics is beset by quantum number conservation constraints. It is thus very hard to conceive that all substructures of the initial baryons should be wiped out and melted into a primitive uniform partonic phase. However, whereas the primary Z^0 decay "string" is of dramatic

longitudinal extension (of about $90 fm$) but of small transverse size directly decaying into the vacuum, the short "strings" of primordial baryonic collisions (of about $3 fm$ length) remain trapped in a large radius cylindrical collision volume of modest aspect ratio (as shown in section 2). The vacuum might be expelled to an outer surface far remote from each primordial string. At the prevailing energy density of several GeV/fm^3 the "string" substructure (precarious anyhow at $\sqrt{s} \approx 3 GeV$) must melt away similarly to the initial baryon structure as the duration of the high density phase (see *Fig. 9*) far exceeds the mean decay time of a free QCD string. The specific significance of the SPS $Pb + Pb$ data concerning hadronic yield ratios thus goes beyond reflecting the fingerprint of the QCD hadronization mechanism (remarkable enough at $\sqrt{s} \approx 17 GeV$): it seems to indicate that bulk partonic volumes hadronize similarly to isolated longitudinal "strings".

Secondly, however, we observe differences in detail that point to the specific features of a large coherent partonic fireball, in comparison to a thin string. We have seen specific suppressions (J/Ψ) and enhancements (strangeness to entropy ratio) in sections 3 and 4. Also, recall *Fig. 8*. An important final hint, supporting the above picture of a bulk parton to hadron phase transition, may be derived from recent NA49 data concerning the *event by event* fluctuation of the K/π ratio in central $Pb + Pb$ collisions [6]. *Fig. 10* shows that this quantity (which indicates both the strangeness to entropy ratio and the overall hadro-chemical makeup of the final state) exhibits no fluctuations other than inflicted by counting statistics as the histogram of single event ratios is nearly identical to the signal derived from artificially Monte Carlo generated mixed events.

Translating this result we may conclude that all central $Pb + Pb$ collision events are identical as to their thermodynamical properties, the observed histogram resulting from sampling statistics only. This observation is made possible by the large acceptance of NA49. It helps to reject, first of all, the critical argument raised oftentimes against thermodynamical analysis, namely that taking ensemble averages fakes thermal patterns which are not a property of individual events. To the contrary these data show that each event permits canonical analysis like a small but macroscopic thermodynamical system, in line with our intention to study partonic or hadronic *bulk matter* properties in such collision events. More specifically (in view of our above discussion) these data support the hypothesis that the apparent hadro-chemical equilibrium state is not caused by hadronic rescattering cascades which would probably lead to a larger dispersion (from the dense interior to the dilute surface regions) as far as the K/π ratio is concerned - and thus to a broad distribution toward lower ratios. On the other hand, if the system reaches above the critical energy density of $\epsilon \approx 1.5 GeV/fm^3$ in most of its volume, the dynamical prehistory gets wiped out because both the much denser central sections and the still dense-enough outer sections of the fireball uniformly encounter QCD hadronization at a fixed energy density (corresponding to $T \approx 185 MeV$) albeit at different hadronization times. The primordial spread in geometry and dynamics thus reflects in a hadronization *time* spread (c.f. *Fig. 8*), accessible to Bose-Einstein correlation study (see next section). However the outcome of hadronization seems to be thus common over the entire fireball volume, in each event: this could explain the data in *Fig. 10*.

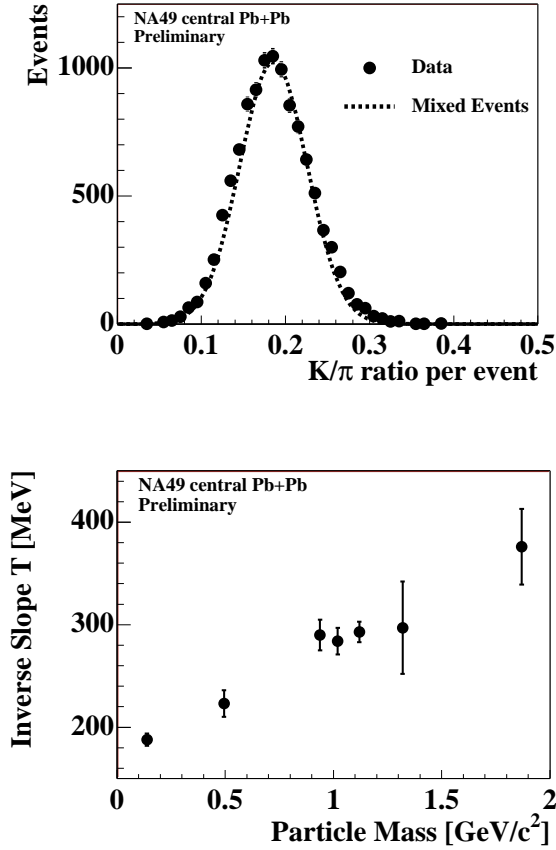


Figure 10: Event by event fluctuation of the K/π ratio in central $Pb + Pb$ collisions in the domain $3.5 < y < 5$ as reported by NA49 [6]. This ratio is obtained from summing negative and positive kaons and pions. The absolute scale is arbitrary (no acceptance corrections applied). The dashed line refers to artificial mixed events.

Figure 11: Increase of the inverse slope parameter T of transverse mass spectra with the hadronic mass, from π to deuterons, in central $Pb + Pb$ collisions [6].

6 Hadronic Expansion Dynamics

Now to the final point: the dynamics of the hadronic expansion. From a combined study of $\pi\pi$ Bose-Einstein (HBT) correlation and final hadronic m_T spectra we learn, first of all (NA49 ref. [28], NA44 ref.[29]), that hadronic expansion is different in $S + S$ and $Pb + Pb$. The transverse energy increases drastically [6, 29], the geometrical HBT parameters increase drastically [28]. Two different classes of hadronic observables are of relevance here. First one observes a breaking of the m_T scaling behaviour predicted in a simple fireball model for the inverse slope "temperatures" (all hadronic species should exhibit similar transverse mass spectral slopes). Fig. 11 shows NA49 results [6] for m_T spectral slopes in $Pb + Pb$ collisions, for hadrons from π to deuterium: the spectral slope parameter increases from 180 to 380 MeV. Similar data have been reported by NA44 [29]. This behaviour has been linked to a collective transverse velocity field [29], prevailing in the expansion. This field "blue-shifts" transverse mass spectra in order of hadronic mass. The final hadronic spectra thus result from superposition of a thermal velocity spectrum, corresponding to the true temperature of hadrons decoupling from strong interaction (freeze-out), and from a radial velocity field blue-shifting that temperature. The origin of the collective velocity field must reside in the overall dynamics of expansion, prior to freeze-out. The spectral data, alone by themselves, do not provide for a clear-cut separation of the two superimposed effects. However, two pion Bose-Einstein correlation (HBT) data allow for an independent analysis of the two combined effects. Combining these two sources of information [28] leads to determination of the thermal,

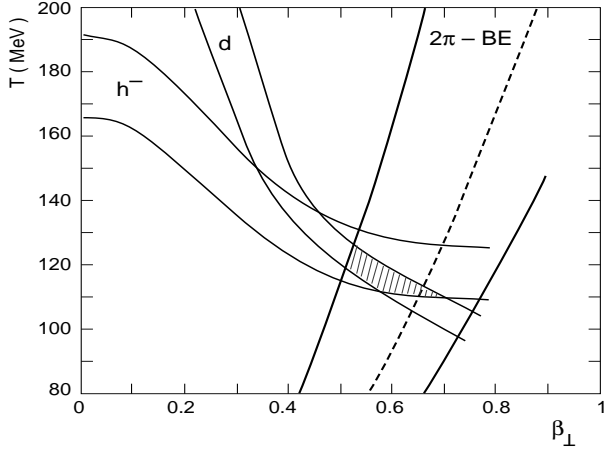


Figure 12: Allowed regions in the plane of freeze-out temperature and transverse collective velocity derived [28] from negative hadron and deuteron m_T spectra, as well as from Bose-Einstein two pion correlation in central $Pb + Pb$ collisions.

and collective velocity field ingredients of the freeze-out stage. *Fig. 12* shows the result of this analysis (for detail the reader is referred to [28] and references therein). The "true" temperature at the end of all strong interaction is about $T \approx 120 \text{ MeV}$, and the system has developed a collective, radially symmetric transverse velocity profile with $\beta_\perp \approx 0.6$ at the freezeout-hypersurface.

From the space-time HBT parameters, the m_T spectra and from our previous arguments about the hadronization temperature, equal to T_c , we may give the following picture of a central $Pb + Pb$ collision:

1. The system originates at about $T = 240 \text{ MeV}$ and $\epsilon = 4 \text{ GeV}/\text{fm}^3$ in the interior and triples its volume until it arrives at $T_c \approx 180 - 190 \text{ MeV}$, $E_c \approx 1.5 \text{ GeV}/\text{fm}^3$. In a spherical approximation this would take about $4\text{-}5 \text{ fm}/c$ if the universal expansion velocity was $\beta \approx 0.5$. In reality the faster longitudinal expansion will shorten this time to perhaps $2 \text{ fm}/c$ [27] (c.f. *Fig. 9*).
2. It hadronizes at T ("Becattini") $\approx 185 \text{ MeV}$ at various baryochemical potentials depending on the reaction system, $S + S$ to $Pb + Pb$, but near $\mu_B = 0.25 \text{ GeV}$. Of course hadronization does not occur instantaneously throughout the volume. It may take $4 \text{ fm}/c$ [27].
3. During expansion from primordial conditions the pion pair emission strength is represented [28] by a Gaussian of mean (overall life-time of the source) $8 \text{ fm}/c$ and sigma (duration of emission time) $4 \text{ fm}/c$: this is shown in *Fig. 13*. Pion pair emission starts right after the formation time of about $1 \text{ fm}/c$ from the surface of the system. I.e. the overall "life-time" starts at this time. The luminosity peaks at about $8 \text{ fm}/c$. These features are in agreement with the Geiger and Srivastava predictions (*Fig. 9*).
4. During this interval, it grows in transverse and longitudinal directions. The transverse *rms* radius [28] increases by a factor of about 2.5. The transverse density thus falls by a factor of 6.25 in a time interval of about $8 \text{ fm}/c$: we observe an "explosive" expansion pattern.
5. It freezes out from strong interaction with $T \approx 120 \text{ MeV}$, the freeze-out phase ending at $\tau \approx 15 \text{ fm}/c$. Collective transverse and longitudinal velocity fields are observed with Gaussian mean velocities at the *rms* points of the density profiles $\beta_\perp \approx 0.55$ and $\eta_\parallel \approx 0.9$ [28].

It is our expectation that this set of data will so severely constrain dynamic expansion models that the conditions at hadronization will be pinned down independent of all other information.

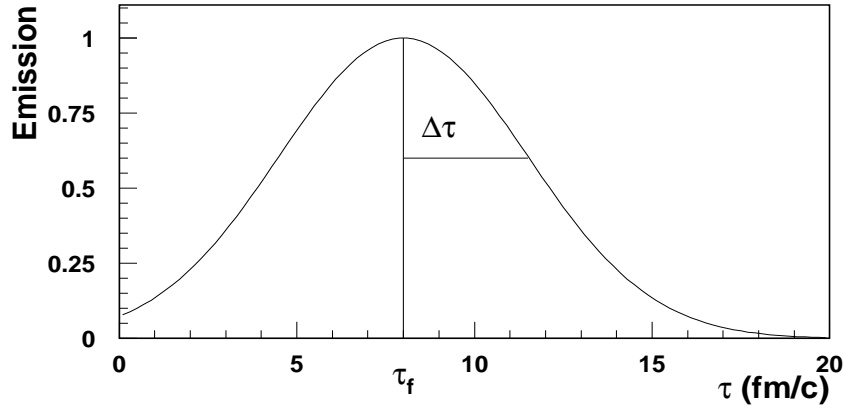


Figure 13: The time profile of pion pair emission from the interaction volume: overall Gaussian life-time τ_f and duration of emission parameter $\Delta\tau$ for central $Pb+Pb$ collisions from Bose-Einstein correlation analysis [28].

7 Discussion

The essential, new point of view in the line of argument pursued here stems from revision of our understanding of the observed hadronic production ratios that suggest $T \approx 185 \text{ MeV}$ in central $Pb+Pb$ collisions similar to LEP Z^0 and W decays to hadrons. We propose this apparent hadronic equilibrium state to be a fingerprint of the non-perturbative hadronization process following Ellis and Geiger [26]. Nuclear collisions at SPS energy reflect the same hadronization properties, which appear not to arise from chemical equilibrium attainment by inelastic rescattering cascades. The change of mechanisms is highlighted by the fact that hadronic rescattering can at SPS energy not even alter the $T \approx 185 \text{ MeV}$ abundance pattern throughout hadronic expansion (due to very fast, "explosive" expansion). Its observation in central nuclear collisions thus lends support to the existence of a transient partonic phase that enters non-perturbative hadronization, after some initial expansion. The implied quantum number coalescence mechanism can be directly tested in hyperon to antihyperon production ratios [23, 30]. Very recent such data [22] by WA97 and NA49 appear to support the evidence for a parton to hadron transition by statistical flavour coalescence.

In summary, I have tried to demonstrate that the majority of CERN SPS data can be coherently understood by assuming that the reaction dynamics of central collisions reaches beyond the hadronic phase throughout the reactions studied yet, i. e. $S+(S, Ag, Au, Pb, W, U)$ and $Pb+Pb$. The primordial energy density in sulphur beam reactions may be just at or above the critical energy density $\epsilon_c \approx 1.5 \text{ GeV}/fm^3$ whereas central $Pb+Pb$ collisions should promote the primordial energy density to far above ϵ_c ; we estimate from J/Ψ suppression data and calorimetry that the density in the extended interior sections of the reaction volume reaches ca. $4 \text{ GeV}/fm^3$, clearly beyond the realm of hadronic matter. For clarity of argument I note that such a primordial passage into a partonic scenario occurs in a non-equilibrium process. It remains to be further investigated whether expansion time scales, partonic relaxation times

etc. conspire favourably for the system to approach the equilibrium QCD state "quark-gluon-plasma" - the object of desire - before expansion brings it back to hadronization. However, bulk hadron production data appear to fix the latter to occur in the vicinity of about 180 MeV : the phase boundary has thus been tentatively located.

* This article is devoted to the memory of Klaus Geiger. Presented at the Erice School of Nuclear Physics, Sept. 1998. To be published in *Progress in Particle and Nuclear Physics*.

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